

HALO TRACING WITH ATOMIC HYDROGEN

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This paper reviews the constraints that can be placed on the shapes of disk galaxies' dark halos using the distribution and kinematics of atomic hydrogen. These data indicate that dark halos are close to axisymmetric, with their axes of symmetry co-aligned with their disk axes. They also appear to be oblate, with shortest-to-longest axis ratios displaying quite a broad range of values from ~ 0.2 to ~ 0.8 . These results are consistent with the predicted shapes of halos in cold dark matter scenarios, but rule out some of the more exotic dark matter candidates. However, the total number of measurements is still depressingly small, and more data are required if halo shape is to become a powerful diagnostic for theories of galaxy formation and evolution.

1 Introduction

Atomic hydrogen (HI) is ubiquitous in the Universe, and the convenient 21cm line means that its kinematics are readily determined, making it an ideal tracer for dynamical studies of the mass distributions of galaxies. The simplest application lies in determining the radial mass profiles in galaxies using their HI rotation curves – indeed, it was through such studies that the existence of dark matter in these systems was first credibly demonstrated.¹ Taking such analyses a stage further, one can start to study the shape of the mass distribution, and hence infer something about the shape of the dark halo. Clearly, this further step requires one to relax the assumption of spherical symmetry in the analysis, and such a step always complicates the analysis. Further, the hydrodynamical nature of the gas can be conveniently ignored when one treats it as a thin axisymmetric disk of material on circular orbits. If one relaxes the imposed symmetry, the orbits of the material in what may now be a triaxial potential become much more complex, making it likely that hydrodynamically-dictated collisions between different components will occur. In addition, since one is now interested in the full three-dimensional structure of the galaxy, one cannot just consider the distribution in the direction in which the gas disk is primarily centrifugally supported; the hydrodynamical processes that support the gas distribution in other directions must also be included in the analysis.

Despite these complexities, we can still obtain at least crude measures of the full three-dimensional shapes of disk galaxies' halos from HI studies. In

Section 2, we look at the constraints that such analyses place on the shapes of halos in the planes of disk galaxies, while Section 3 looks at the corresponding data perpendicular to their disk planes.

2 Halo Shapes in the Planes of Galaxies

As mentioned above, the key to studying galaxies' mass distributions is that the orbits of material are dictated by the gravitational potential. If the mass distribution is not spherically symmetric, one would expect this to show up as a corresponding absence of symmetry in the orbits. One problem in studying disk galaxies is that it is not entirely straightforward to establish their symmetry: a disk that appears elliptical may do so because it is intrinsically non-symmetric, but it could equally be an axisymmetric disk that is not viewed face on. Thus, the simplest use of HI in this context is to establish a disk's orientation, by using the fact that the width of the 21cm emission integrated from the entire galaxy depends on how close the galaxy is to face on. Figure 1 shows a simple implementation of this approach, where I have plotted apparent optical ellipticity versus HI line width for a sample of nearby galaxies. Those galaxies with very small line widths, which must lie close to face-on, all have very low ellipticities, implying that disk galaxies are close to round in shape, and hence that the potential in the disk plane is nearly axisymmetric. Fitting this data distribution with an elliptical disk model places a constraint on the mean ellipticity in the gravitational potential of $\epsilon < 0.1$.

In fact, localized star formation, spiral arms, etc, may render a face-on globally-circular disk somewhat elliptical in appearance, so this plot can really only provide an upper limit on the true ellipticities of disks; a better analysis² using near infrared data to avoid most of this problem places an even tighter constraint on the ellipticity of the potential in the plane, yielding a value of $0.045^{+0.03}_{-0.02}$.

A related constraint can be derived by noting the tightness of the Tully-Fisher relation. Using infrared photometry, the relationship between the inclination-corrected HI line widths and absolute magnitudes of disk galaxies shows a scatter of only ~ 0.25 magnitudes.³ If disk galaxies were intrinsically elliptical, then there would be two new contributions to the scatter: first, if the apparent ellipticity were used to estimate a galaxy's inclination, then non-circular disks would lead to erroneous inclination corrections in the HI line width; and second, the non-circular motions of the HI gas would mean that the relationship between observed line width and average circular speed would vary depending on the orientation of the disk's major axis, again blurring the relation. A study of these effects⁴ placed a limit on the average ellipticity of the potential in the

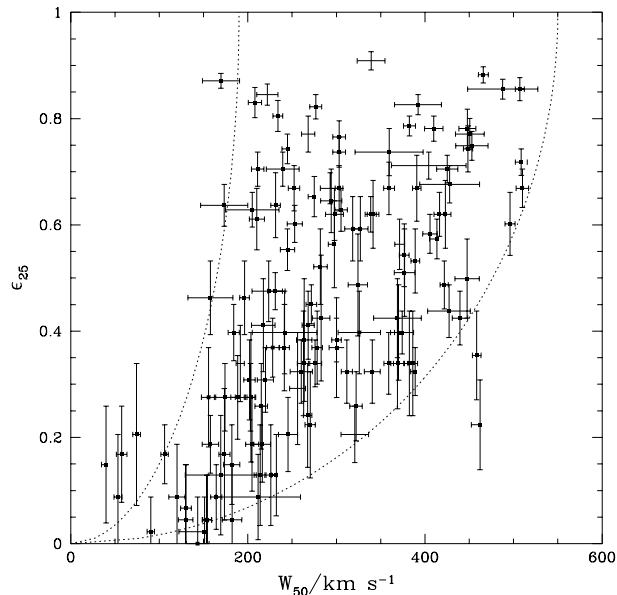


Figure 1: The ellipticities of disk galaxies as determined at the $25 \text{ mag arcsec}^{-2}$ isophote, plotted against the full width half maximum of their HI line widths. The data were drawn from the LEDA database, and consist of all galaxies of types Sa – Sc that are bright in HI ($M_{21} < 13$), and that have their axis ratios determined to better than 10%. Since ellipticity is defined to be positive, there will be a bias in this plot that increases the mean ellipticity where it is close to zero. The lines show where thin axisymmetric disks with two different rotation speeds should lie on this plot.

planes of disk galaxies of $\epsilon < 0.1$. Such an analysis complements what we learn from the optical disk shape analysis, since the HI disks generally lie at larger radii: we thus have some indication that the shape of the mass distribution does not vary significantly over a range in radii.

In addition to these global techniques for modeling the average properties of the gravitational potentials of an ensemble of galaxies, one can also study the kinematics of HI in individual galaxies in order to measure their halo shapes. In particular, the HI rings found around some galaxies make exceptional probes of these systems' shapes. For example, a study⁵ of the HI gas ring around the early-type galaxy IC 2006 showed that the line-of-sight velocity as a function of azimuth around the ring could be accurately modeled if the ring were intrinsically circular. Formally, this analysis measures the el-

lipticity of the potential at the radius of the ring as $\epsilon = 0.012 \pm 0.026$. These techniques can be extended to studies of complete disks of HI or H α emission, essentially by fitting the gas intensity and line-of-sight velocity at each point using a series of tilted rings. Such studies^{6,7} also indicate that the potential is close to axisymmetric in the disk plane of normal spiral galaxies, with typical values of $\epsilon \sim 0.05$, although there seem to be a few galaxies with ellipticities as large as $\epsilon \sim 0.2$.⁷

3 Halo Shapes Perpendicular to the Planes of Galaxies

Perpendicular to the planes of disk galaxies, constraints on the shapes of halos are rather harder to come by. One obvious approach is to look at polar ring galaxies, in which a ring of material, usually containing HI, orbits around the pole of a disk galaxy. In such a fortuitous arrangement, one can use the type of analysis described above to model the kinematics of the ring, and hence assess the shape of the potential in this direction. Although such analyses provide some of the most reliable information on the shapes of halos,⁸ there is one important caveat associated with these studies: polar ring systems are not normal galaxies. The ring probably formed in a significant merger, and it is quite likely that such a cataclysmic event will also alter the structure of the halo in the resulting composite system. It is therefore not obvious that the shapes of halos in these systems are representative of the general population.

A more generally applicable technique involves looking at the distribution of gas in a disk galaxy perpendicular to its plane.⁹ The thickness of the gas layer is dictated by the hydrostatic balance between the internal turbulent motions of the gas, and the pull of gravity towards the plane: the more mass there is close to the plane, the thinner the distribution into which the gas is gravitationally squeezed. Thus, if one uses the rotation curve to derive the radial distribution of mass, one can then determine how closely this mass is concentrated toward the galactic plane by the observed thickness of the gas layer. Since the density of the dark halo drops with radius, the force confining the gas layer decreases, and so one characteristically sees a “flaring” in the HI layer at large radii; it is exactly how the layer thickness increases with radius that provides the constraint on halo flattening.

In the mid-1990s, this technique was successfully applied to a few galaxies,^{9,10} but there were a number of initial doubts over its validity. In particular, the hydrodynamical behavior of the gas means that the physics is nowhere near as clear cut as for a pure gravitational problem: other forces such as cosmic ray and magnetic field pressures could well be significant, and it is not even obvious quite what velocity dispersion should be associated with the turbulent

motions of gas clouds in the hydrostatic equilibrium equation. These concerns were compounded when both of the initial applications (to NGC 891 and NGC 4244) implied highly flattened dark halos with shortest-to-longest ratios in the density distribution of ~ 0.3 . These results were only marginally consistent with those derived using other observational techniques (such as the study of polar ring systems), and were not at all what most theories suggested.

In order to test the validity of the method, we decided to apply it to the Milky Way’s HI layer, as in our own galaxy there are other techniques that one can use to determine the halo shape. The first requirement for such an analysis is a reliable measure of the Galaxy’s rotation curve. In the inner Galaxy, this is readily determined from HI data by the tangent point method, but at Galactic radii larger than the Sun’s (where the crucial flaring in the gas layer occurs), this method is not available. Fortunately, an alternative technique has been developed,¹¹ which assumes only that the thickness of the Galactic gas layer does not vary with azimuth around the Galaxy, and that the material is moving around circular orbits. With these assumptions, one can solve simultaneously for both the rotation curve and the thickness of the layer as a function of radius – both the ingredients required for determining the shape of the dark halo. Applying the gas layer technique to these data resulted in a measurement of the Milky Way’s halo shortest-to-longest ratio of ~ 0.7 .¹² This result showed that the gas layer flaring method does not always result in the systematically highly-flattened halos that the first two applications had, apparently by chance, returned. Further, we were able to show that the result was consistent with the constraint on halo flattening that one can derive from an analysis of stellar kinematics perpendicular to the Galactic plane in the Solar neighborhood: in that case, one uses a similar hydrostatic balance between the stellar velocity dispersion and the pull of gravity toward the plane to derive the total mass near the plane in the Solar neighborhood; after subtracting the contribution from stars and gas in this region, one obtains the amount of dark matter, and hence can derive the flattening of the halo.

Returning for a moment to the shape of the halo in the planes of disk galaxies (Section 2), it is worth noting that the technique described above for determining the Milky Way’s rotation curve depends on the assumption of axisymmetry. If this assumption turns out to be invalid, one makes a different error in the derived rotation curve than one would make using more conventional standard candle methods for estimating the rotation curve. Interestingly, there is a small difference between the rotation curves derived by these two methods, which has been used¹³ to estimate that the potential in the plane of the Milky Way has an ellipticity of $\epsilon \sim 0.07$.

Further confirmation that the gas layer flaring method does not return

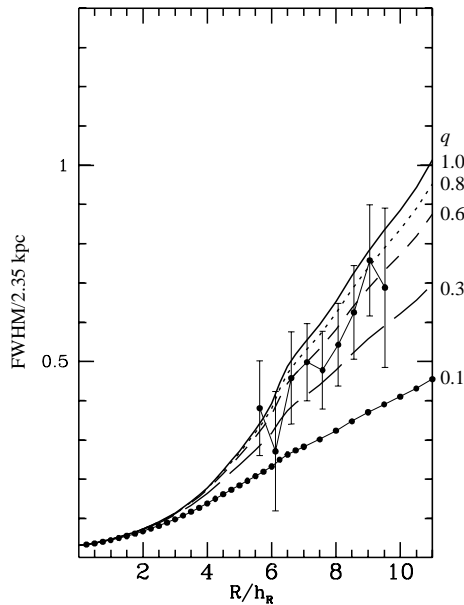


Figure 2: The thickness of the HI layer in NGC 3198. Observed values¹⁴ have been fitted by dark halo models with a variety of longest-to-shortest axis ratios, q .

systematically highly flattened halos has come from recent work that we have undertaken on NGC 3198. As the preliminary results presented in Figure 2 show, the variation in the thickness of the HI layer with radius in this galaxy is not consistent with a highly flattened halo, but favors a shortest-to-longest axis ratio of ~ 0.6 .

4 Summary

Studying different aspects of the kinematics of HI gas in disk galaxies provides us with a range of tools for probing the overall distribution of mass in these systems. Since the gas extends to large radii where the mass is dominated by dark matter, these tools are well suited to studying the shapes of galaxies' dark halos. In the planes of disk galaxies, the distribution seems to be very close to axisymmetric, with some indications of an ellipticity in the potential of ~ 0.05 . Perpendicular to the plane, a broader range of flattenings is apparent: as Figure 3 summarizes, shortest-to-longest axis ratios ranging from ~ 0.2 to

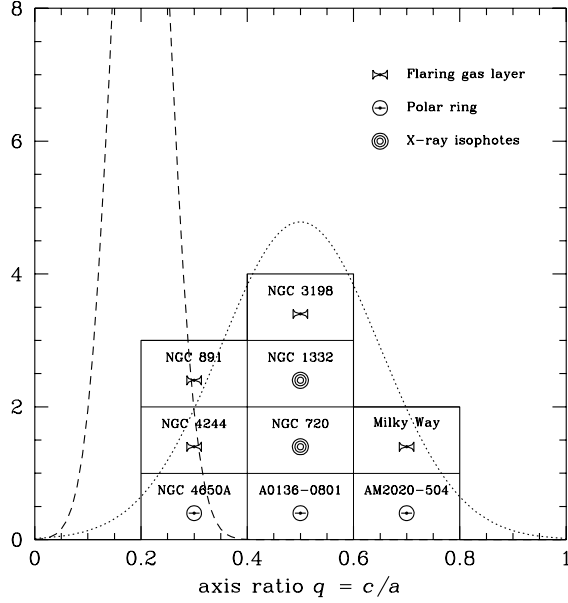


Figure 3: Distribution of measured shortest-to-longest axis ratios of galaxies' dark halos using the available credible techniques. The name and method for each galaxy is indicated. The dotted line shows the distribution predicted by cold dark matter simulations, while the dashed line shows the distribution expected if cold molecular gas were to make up the dark matter.

~ 0.6 are all found. Further, the results from HI seem to be consistent both with those obtained from studies of polar ring galaxies (so the fears expressed in Section 3 seem to be unfounded) and those derived from the X-ray isophotes of elliptical galaxies.¹⁵

Using the data in Figure 3, one can begin to make quantitative comparisons with theory. As the figure shows, the observations are quite compatible with the predicted halo flattenings that should occur when galaxies form in standard cold dark matter cosmologies,¹⁶ but are inconsistent with the highly-flattened mass distribution that one would predict if all the dark matter were made up from cold molecular material.¹⁷ However, perhaps the most notable fact apparent from Figure 3 is quite how few reliable measurements of halo shape have actually been made. The challenge for the next few years is to populate this histogram with sufficient new data for it to become a powerful diagnostic for testing theories of galaxy formation and evolution.

Acknowledgements

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